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Temperature Variations and Chemical Abundances in Planetary Nebulae

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Abstract. In this review we present a brief discussion on the observational evidence in favor of the presence of temperature variations, and conclude that many planetary nebulae show spatial temperature variations that are larger than those predicted by 1D static chemically homogeneous photoionization models. To determine accurate chemical abundances it is necessary to know the cause of these temperature variations and several possibilities are discussed. The importance of this problem is paramount to test the models of stellar evolution of low and intermediate mass stars and of the chemical evolution of galaxies. We conclude that the proper abundances for chemically homogeneous PNe are those derived from recombination lines, while for the two-abundance nebular model the proper heavy element abundances relative to hydrogen are those derived from visual and UV collisionally excited lines adopting the t^2 values derived from T_e([O III]) and T_e(Balmer).

Keywords. atomic data, shock waves, stars: abundances, planetary nebulae: general

1. Overview

Recent reviews on the presence of temperature variations in PNe have been presented by Esteban (2002), Liu (2003, 2006), and Torres-Peimbert & Peimbert (2003). Of the well observed PNe about one third can be fitted reasonably well by 1D static chemically homogeneous photoionization models, but two thirds show temperature variations that are substantially larger than those predicted by simple photoionization models. In this paper we review further evidence in favor of the presence of large temperature variations in PNe. We discuss possible causes for these variations and their effect on the determination of chemical abundances of PNe. We discuss the proper procedure to obtain accurate abundances for chemically homogeneous and for chemically inhomogeneous PNe.

2. Temperature determinations

Peimbert (1967, 1971) found that the determinations of T_e([O III]), the temperatures based on the $I(4363)/I(5007)$ ratio, are considerably larger than the determinations of T_e(Balmer), the temperatures based on the intensity ratio of the Balmer continuum to a Balmer recombination line; he interpreted this result as being due to the presence of temperature variations over the observed volume. To study this problem, Peimbert defined the mean square temperature variation, t^2; typical simple photoionization models yield t^2 values in the 0.003–0.015 range. Peimbert and collaborators, also developed equations to derive the abundances for chemically homogeneous nebulae with $t^2 > 0.000$ (Peimbert 1967; Peimbert & Costero 1969, Ruiz *et al.* 2003, Peimbert *et al.* 2004). The large differences between T_e([O III]) and T_e(Balmer) have been confirmed by several authors for a large number of PNe (e.g. Liu & Danziger 1993; Zhang *et al.* 2004).

Peimbert, Storey, & Torres-Peimbert (1993) based on the computations by Storey (1994) were the first to obtain larger O^{++}/H^{+} values from oxygen recombination lines than from collisionally excited lines under the assumptions of $t^2 = 0.000$ and of chemical homogeneity. Most PNe show this difference which has been usually called the abundance discrepancy factor defined by: adf(O^{++}/H^{+}) = $(O^{++}/H^{+})_{RL}$ / $(O^{++}/H^{+})_{CEL}$, (e. g. Liu 2006, and references therein). The adf(O^{++}/H^{+}) value is larger than predicted by simple photoionization models for about two thirds of the well observed PNe.

A similar abundance difference for C^{++}/H^{+} has been obtained by Peimbert, Torres-Peimbert, & Luridiana (1995a) based manly on the line intensities compilation by Rola & Stasińska (1994). Peimbert *et al.* (1995a) compared the C^{++}/H^{+} abundances derived from the C II λ4267 recombination line with those derived from the C^{++} $\lambda\lambda$1906, 1909 collisionally excited lines. Again about one third of the adf(C^{++}/H^{+}) of the well observed PNe might be explained by simple photoionization models but two thirds present values too large to be reproduced by these models.

Zhang *et al.* (2005) have obtained large T_e([O III]) $-$ T_e(He I) differences for 48 PNe that cannot be explained by simple photoionization models. In section 4.2 we discuss their results.

3. Possible sources of temperature variations

Torres-Peimbert & Peimbert (2003) presented seven mechanisms as possible sources of temperature variations; in what follows we will mention additional results in favor of some of these mechanisms.

Deposition of mechanical energy: The central stars of PNe inject mechanical energy into the expanding shells by means of stellar winds, bipolar flows, multipolar flows, and asymmetrical ejections; these processes produce shocks, turbulence, and an increase of the expansion velocity of the shell with time. These processes are more important for some objects than for others and might be responsible for the spread in the observed t^2 values. Guerrero *et al.* (2005) and Guerrero, Chu, & Gruendl (2006) found that the following PNe are strong X-ray emitters: BD+30° 3639, NGC 40, NGC 2392, NGC 3242, NGC 6543, NGC 7009, and NGC 7027; they also argue that this emission is due to shocks produced by fast winds or bipolar flows. Rowlands, Houck, & Herter (1994) derived T_e([Ne V]) $\sim$ 50,000 K for NGC 6302 and NGC 6537; they also computed photoionization models and were not able to produce temperatures higher than 20,000 K and reached the conclusion that these temperatures were indicative of shock heating. Peimbert *et al.* (1995a) found that the following PNe with large velocity dispersions also show large temperature variations: NGC 2392, NGC 2371-2, NGC 2818, NGC 6302, and Hu 1-2; the last four are bipolar Type I PNe. Medina, Peña, & Stasińska (2006) found, from a sample of 47 PNe, that the velocity of expansion of the shell increases with age indicators, for example $\langle v_{exp} \rangle$ is larger for low density nebulae and it is also larger for nebulae with higher temperature stars. Furthermore by studing the line profiles Medina *et al.* (2006) find that a substantial fraction of the material shows turbulent motions.

Chemical inhomogeneities: See section 4.2 and the review by Liu (2006).

Time dependent ionization: When a photoionization front passes through a nebula it heats the gas above the steady state value and some time is needed to reach thermal equilibrium. In the presence of localized density variations or a density gradient, this process produces large temperature variations and might explain the presence of hot external halos in PNe (e.g. Tylenda 2003, Sandin *et al.* 2006). When the stellar ionizing flux decreases, or the density distribution along the line of sight changes, the outer regions of a nebula might become isolated from the stellar radiation field and will cool down before fully recombining, creating cold partially ionized outer regions; this might explain the low T_e(Balmer) values derived by Luo & Liu (2003) in the outer regions of NGC 7009.

Density variations: Extreme density variations are present in most PNe, as can be seen from optical images. For steady state photoionization models density variations are not very important, but for time dependent processes the regions of higher density will reach equilibrium sooner than those of lower density.

Deposition of magnetic energy: No specific models have been proposed yet for this mechanism.

Dust heating: Stasińska & Szczerba (2001) have analyzed the effects of photoelectric heating by dust grains in photoionization models of PNe. This effect might be important in nebulae with large density variations. This suggestion has not been tested yet for a specific model on any given PN.

Shadowed regions: Due to the presence of molecular globules inside NGC 7293 and NGC 6720, two nearby PNe, their presence is expected in many PNe. According to Huggins & Frank (2006), the covering factor of the globules in NGC 7293 amounts to about 5%. The ionization of the gas shadowed by the globules will be produced by diffuse radiation, and consequently, the temperature of the shadowed gas will be a few thousand degrees lower than that of the material that is directly ionized by the central star (Mathis 1976). This mechanism alone might produce t^2 values around 0.01 in PNe of the type of NGC 7293 and NGC 6720.

To discriminate among the different possibilities, it is important to understand the signature of each process on the temperature and density distributions. Mechanical energy deposition, an increase in the local ionizing flux, and magnetic energy deposition will produce localized high-temperature regions relative to simple photoionization predictions; while shadowed regions, the decrease of the local ionizing flux, and the presence of metal-rich inclusions will produce localized low-temperatures regions relative to simple photoionization predictions.

4. Forbidden or recombination line abundances?

4.1. *Chemically homogeneous case*

Abundances correspond to those derived from recombination lines; if forbidden lines are used, a t^2 different from 0.000 has to be adopted. In what follows we present evidence in favor of chemical homogeneity for most PNe.

From chemical evolution models of the Galaxy it has been found that in the solar vicinity about half of the C enrichment of the ISM is due to low and intermediate mass stars that end their lives as white dwarfs, and the rest is due to SN of Type II (e. g. Carigi *et al.* 2005). Moreover according to other models most of the C enrichment is due to low and intermediate mass stars (e. g. Matteucci 2006). Carigi (2003) has shown that the C/H values derived from C II recombination lines are in agreement with these models, while the C/H values derived from the $\lambda\lambda$1906 and 1909 collisionally excited lines, under the assumption of T_e([O III]) and $t^2 = 0.000$, imply lower C yields than those needed by the Galactic chemical evolution models.

Esteban *et al.* (2005), based on recombination lines of C II and O II of Galactic H II regions, have determined for the ISM of the solar vicinity that $12 + \log \mathrm{O/H} = 8.77\pm0.05$ and $12 + \log \mathrm{C/H} = 8.67\pm0.07$. These values are in excellent agreement with the Asplund, Grevesse, & Sauval (2005) solar values (see Table 1), considering that since the Sun was formed the increase in the ISM abundances of these elements has been of 0.13 dex in

Table 1. Stellar and Nebular Abundances for NGC 6543

$N(X)/N(\mathrm{H})$	CELs	RLs	Central Star	Solar Values
He/H	...	0.117 ± 0.004	0.11 ± 0.01	...
12 + log C/H	8.2-8.5	8.90 ± 0.10	9.0 ± 0.1	8.39 ± 0.05
12 + log O/H	8.86 ± 0.10	9.15 ± 0.10	9.1 ± 0.1	8.66 ± 0.05

References: C/H Rola & Stasińska (1994), Peimbert, *et al.* (1995a), Wesson & Liu (2004); O/H(FL) and all RLs Wesson & Liu (2004), central star Georgiev *et al.* (2006); solar values Asplund, Grevesse, & Sauval (2005).

O/H and 0.29 dex in C/H; the increases in C/H and O/H are those predicted by Galactic chemical evolution models by Carigi *et al.* (2005).

In Table 1 we present the stellar abundances of NGC 6543 based on a non-LTE model by Goergiev *et al.* (2006), and compare them with those derived from recombination and forbidden lines of the gaseous nebula. The recombination O^{++} abundance is based only on the multiplet 1 of O II. The agreement between the nebular recombination line abundances and the stellar abundances is excellent, while the forbidden line abundances are about a factor of two to four smaller than the stellar ones. This result is in favor of the idea that the recombination line abundances are the proper ones for this object.

The O/H value for the central star of NGC 6543 is higher than the solar value, see Table 1. There are three factors that might help to explain the difference: a) the Sun was formed 4.5 Gyr ago and, as mentioned above, the C/H and O/H values of the ISM have increased during this period, therefore we would expect PNe with progenitor masses greater than 2 $\mathrm{M}_\odot$ to have been formed when the ISM had abundances greater than solar; b) a fraction of the H has been converted into He increasing the C/H and O/H ratios, this is a small effect and is in the 0.02 to 0.06 dex range; and c) some intermediate mass star models predict an increase in the O/H ratio; Marigo, Bressan, & Chiosi (1996) obtain an increase of about 0.2 dex in the O/H ratio for stellar models in the 1.83 to 2.5 $\mathrm{M}_\odot$ mass range with Z=0.008. It is clear that accurate abundances for the atmospheres of the central stars of PNe are needed to test the models of stellar evolution.

Liu *et al.* (2001) presented a strong correlation between the adf($\mathrm{O}^{++}/\mathrm{H}^{+}$) and T_e([O III]) $-$ T_e(Balmer) and mention that this correlation strongly supports the idea that temperature variations are real. Similarly, from the adf($\mathrm{C}^{++}/\mathrm{H}^{+}$) values by Peimbert *et al.* (1995a) and others in the literature and the T_e(Balmer) values by Zhang *et al.* (2004), a strong correlation between the adf(C^{++}) and T_e([O III]) $-$ T_e(Balmer) is found, a result that also supports the presence of temperature variations.

From the relative intensities of the lines of multiplet 1 of O II it is possible to obtain N_e(O II) (Ruiz *et al.* 2003; Peimbert & Peimbert 2005, Bastin & Storey 2006). The N_e(O II) values can be compared with the N_e(Balmer) values obtained from Zhang *et al.* (2004). In Table 2 we present the densities obtained from [Cl III], O II, and H I lines for five PNe with relatively high adf(O^{++}) values (see Liu 2006, and references therein). The N_e(O II) values were obtained from the equations presented by Peimbert & Peimbert (2005); these equations were derived from a calibration based on H II regions. The N_e(O II) values presented in Table 2 probably are slightly higher than the real ones because the temperatures of the H II regions used for the calibration are larger than those of the PNe in Table 2; therefore the N_e(O II)values presented in Table 2 should probably be reduced by 0.1 to 0.2 dex due to the temperature difference. The equations determined by Ruiz *et al.*, based on a fit to PNe and H II regions, yield N_e(O II) values about 0.25 dex smaller than those presented in Table 2. The N_e(O II) values are in good agreement with the N_e(Balmer) values supporting the idea that these objects are

Table 2. Electron Densities (cm^{-3})

Object	log N_e[Cl III]	log N_e(Balmer)	log N_e(O II)
NGC 6153	3.6 ± 0.2	3.8 ± 0.2	3.9 ± 0.3
NGC 6543	3.7 ± 0.1	3.8 ± 0.2	4.0 ± 0.4
NGC 7009	3.5 ± 0.2	3.8 ± 0.1	4.2 ± 0.3
M1-42	3.2 ± 0.1	3.7 ± 0.2	3.9 ± 0.3
M2-36	3.7 ± 0.1	3.8 ± 0.1	4.0 ± 0.3

N_e [Cl III], N_e(O II) Peimbert & Peimbert (2005, and references therein); N_e (Balmer) Zhang *et al.* (2004).

chemically homogeneous. The N_e([Cl III]) values are smaller than the N_e(Balmer) values, which is expected in the presence of a medium with density and temperature variations.

Chemically inhomogeneous nebulae can be produced by H-poor stars that eject material into H-rich nebulae. That is the case of A30 and A78 (Jacoby 1979; Hazard *et al.* 1980; Jacoby & Ford 1983; Manchado, Potasch & Mampaso 1988; Wesson & Liu 2003). This type of situation might occur in those cases where the central star is H-poor. According to Gorny & Tylenda (2000) about 10% of the central stars of PNe are H-poor; while, from the results of the Sloan project, based on 2065 DA and DB white dwarfs, Kleinman *et al.* (2004) find that 1888 are non-magnetic DAs and 177 are non-magnetic DBs. From these numbers, we conclude that about 10% of Galactic PNe have a H-poor central star, and might show He, C, and O rich inclusions in their expanding shells. We consider it unlikely for PNe with H-rich central stars to have significant amounts of H-poor material in their associated nebulae.

4.2. *Chemically inhomogeneous case*

It has been proposed that many PNe are chemically inhomogeneous (e.g. Liu 2006 and references therein). In this proposal, the two-abundance nebular model, PNe present two components: a) the low density component, that has most of the mass and is relatively hot, emits practically all the intensity of the H lines and of the forbidden lines in the visual and the UV, and part of the intensity of the He I lines, and b) the high density component, that has only a small fraction of the total mass, is relatively cool, H-poor, and rich in heavy elements, and emits part of the He I and of the recombination line intensities of the heavy elements but practically no H and no heavy element collisionally excited lines.

In favor of the two-abundance nebular model is that it provides an explanation for the observed T_e(Balmer) $-$ T_e(He I) differences, but it does not provide an explanation for the temperature variations responsible for the difference between T_e([O III]) and T_e(Balmer). The main evidence for the two abundance nebular model has been provided by Zhang *et al.* (2005) who found an average difference of T_e(Balmer) $-$ T_e(He I) $= 4000$ K from the ratio of the $\lambda6678$ to $\lambda7281$ recombination lines of He I in 48 PNe.

The abundances of the low density component are the ones needed for studies of the chemical evolution of galaxies and of low and intermediate mass stars; therefore we will discuss its abundances. For the low density component the forbidden lines with $t^2 = 0.000$ provide a lower limit and the recombination lines provide an upper limit to the real abundances relative to H. The t^2 formalism applies to any type of gaseous nebulae, but the equations to derive abundance ratios by Peimbert & Costero (1969), Ruiz *et al.* (2003) and Peimbert *et al.* (2004) assume chemical homogeneity; in the two-abundance model, the low density component is chemically homogeneous, thus its abundance can be computed from this formalism using a t^2 that is representative of this volume; since we

Table 3. Electron Temperatures (K)

Object	T_e([O III])	T_e(Balmer)	T_e(He I)^a	T_e(He I)^b	T_e(He I)^c
NGC 6572	10500 ± 300	10300 ± 1000	9800 ± 600	7100 ± 500	8690 ± 1200
NGC 6803	10000 ± 300	8500 ± 400	8500 ± 500	6900 ± 400	5000 ± 1100
NGC 7009	10000 ± 300	7200 ± 400	8000 ± 400	6800 ± 400	5040 ± 800
NGC 7027	13000 ± 300	12000 ± 400	10000 ± 600	8200 ± 600	10360 ± 1100
NGC 7662	13000 ± 300	12200 ± 600	9500 ± 600	9200 ± 700	7690 ± 1650
Hu 1-2	18900 ± 300	20000 ± 1200	12900 ± 600^d	...	11500 ± 1500

T_e([O III]), T_e(He I)^{a,b,d} Peimbert *et al.*(1995b); T_e(Balmer) Zhang *et al.* (2004); T_e(He I)^c Zhang *et al.*(2005); a) 3889,4471,7065; b) 3889,4471,10830; c) 6678,7281; d) 4471,5876,6678.

don't expect the high density component to have neither relevant hydrogen emission (it contains very little hydrogen) nor relevant [O III] $\lambda\lambda$4363, 5007 emission (it is too cold), the t^2 that can be determined from T_e(Balmer) and T_e([O III]) will only be representative of this volume and the abundances determined from Hβ, [O III] λ5007, and this t^2 will have no contamination from the emission of the very small high density region. Therefore the proper abundances for the heavy elements are those derived from the forbidden lines adopting the t^2 value derived from the combination of T_e(Balmer) and T_e([O III]), for those PNe with most of their oxygen in the O^{++} stage. If these abundances are in agreement with those derived from recombination lines it means that the nebula is chemically homogeneous.

In Table 3 we present temperature values for six very bright PNe derived from four different sets of He I recombination lines and compare the results derived by Zhang *et al.* (2005) with those derived by Peimbert, Luridiana, & Torres-Peimbert (1995b). The best comparison between T_e(Balmer) and T_e(He I) is provided by objects where most of the He is in the form of He$^+$, because then the He I lines and the H I lines originate in the same volume. For NGC 6572, NGC 6803, and NGC 7009 most of the He is in the He$^+$ stage, and the T_e(Balmer) and T_e(He I) values are practically the same when T_e(He I) is derived from $\lambda\lambda$3889, 4471, and 7065, contrary to the results derived from λ6678 and λ7281, and in favor of a homogeneous chemical composition for these three objects. Alternatively the results derived from $\lambda\lambda$3889, 4471, and 10830 are intermediate between those derived from $\lambda\lambda$3889, 4471 and 7065, and those derived from λ6678 and λ7281 providing support for the two-abundance nebular model. For the other three PNe the three sets of He I lines clearly indicate that T_e(He I) is smaller than T_e(Balmer), but in these three PNe a large fraction of He is in the He^{++} region where a higher temperature is expected and where a fraction of the Balmer line emission originates, particularly in the case of Hu 1-2. The differences in the T_e(He I) values derived from different sets of He I recombination lines need to be sorted out.

5. Conclusions

We consider that our knowledge on the density and temperature distributions and on the chemical composition of PNe will increase considerably from the study of the four following problems.

The N_e(O II) values derived from the O II lines of multiplet 1, like those presented in Table 3, need to be determined again based on the atomic physics computations by Bastin & Storey (2006). Objects with small He^0 and He^{++} fractions and with most of their O in the O^{++} ionization stage will be particularly useful; those objects of this group with N_e(O II) $\sim$ N_e(Balmer) will be chemically homogeneous, while those with N_e(O II) $>$ N_e(Balmer) will be chemically inhomogeneous.

The idea that there are high density He^+ regions embedded in low density H rich material might be tested by deriving T_e(He I), N_e(He I), and τ(3889) based on accurate measurements of at least 10 different He I lines in relatively low density PNe without substantial He^0 and He^{++} regions. Those objects with N_e(He I) $\sim$ N_e(Balmer) will be chemically homogeneous, while those with N_e(He I) $>$ N_e(Balmer) will be chemically inhomogeneous.

There are at least seven possible mechanisms as sources of temperature variations. From the theoretical side, it is important to model the signature of each process on the temperature and density distributions. From the observational side, the combination of 3D kinematical models with high spectral resolution data, like those presented by Barlow *et al.* (2006), might permit to derive temperature and density distributions and consequently to single out the main mechanism responsible for the temperature variations in a given object.

Finally, accurate H, He, C, and O abundances of H-rich central stars, like those obtained by Georgiev *et al.* (2006) for NGC 6543, are needed to compare them with those nebular abundances derived from permitted and forbidden lines.

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